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Solid state amplitude modulated acoustic anemometer

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SOLID STATE AMPLITUDE MODULATED ACOUSTIC ANEMOMETER

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UNITED STATES
NAVAL POSTGRADUATE SCHOOL

THESIS

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ABSTRACT

In recent years considerable research has been directed toward developing wind measuring devices that eliminate the need for moving parts. This thesis proposes a method using amplitude modulated ultrasound to provide greater dynamic wind velocity measurement range and at the same time decrease the cost and complexity of the system. The theory, design, and implementation of the system are presented and the limited results are discussed.

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I. BACKGROUND

Considerable work has been done in recent years to develop a method of wind measurement which has no moving parts, a fast response time so as to serve as a gustmeter, and accuracy commensurate with or better than existing cup type anemometers. The acoustic method of measurement of the rate of movement of an air mass has proved successful and exhibits many advantages over the mechanical methods of wind measurement:

1. Increased reliability due to the absence of light weight, low friction moving parts.
2. A provision for deicing could be readily developed.
3. Due to the absence of moving parts, the low inertness provides a fast response time which allows the instrument to record accurately the extent of wind gusts.
4. The system normally allows the choice of the readout in the wind vector components or in the resultant composite wind vector.
5. The instrument is an absolute measuring device and its calibration can be closely calculated from theory.
6. A system can be designed which would measure wind velocity in three degrees of freedom thereby giving a complete air movement picture at all instants of time.

Micrometeorologists have found the existing acoustic anemometers quite useful in their research of winds and turbulence in the atmospheric boundary layer that do not exceed about ± 5 meters per second. However, it has been suggested that sonic anemometers by used for such applications as wing loading and turbulence measurements on a missile. For applications such as this a much greater dynamic range of operation is required than that which suffices for micrometeorological research. Also the total dimensions of the transducer array must necessarily be small. These are normally conflicting requirements since large dynamic measurement ranges dictate low frequencies and low frequencies normally require relatively large transducers and this in turn demands large transducer to transducer spacing because of the attendant eddy current interference caused by air flow about these large transducers.

The acoustic anemometer described in this thesis was designed and constructed with a threefold purpose in mind:

1. Previous acoustic anemometers have used vacuum tube circuitry, and consequently were quite bulky and consumed relatively large amounts of power. In the acoustic anemometer described in this thesis, solid state circuitry was used throughout in order to reduce the overall size of the unit and greatly reduce the power consumed.

2. The transducer array was arranged in the confi-

guration proposed by Kaimal.[1] The four receiving transducers are placed in a horizontal plane and directed toward the transmitting transducer which is directed downward. The transmitting transducer is positioned equidistant from the four receivers but displaced vertically above the plane of the receivers by a distance equal to one half the distance between two diagonally opposite receivers. (See Figure 1) "This arrangement significantly cuts down interference to the natural airflow along the acoustical paths because of the acoustic array, yet permits a very simple approach to circuit design. There are no adjustments to be made prior to operation and the output signals are voltage analogs of the two wind components, easily adaptable for a variety of recording techniques."[2]

3. The third, and most interesting, purpose of this thesis is to investigate the feasibility of using amplitude modulated ultrasonic waves for wind measurement. This method may lead to much greater freedom of choice of transducers, transducer separation, and maximum wind velocity measurable. The basis of this problem is that for minimum disturbance of the wind

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[1] Reference 3, p. 2-5.

[2] Reference 3, p. 2.

stream, very small transducers are desired; these small transducers, in turn, require high frequencies. However, as the required frequency is increased, all other things being equal, the maximum wind measurable is lowered. The amplitude modulation method of this thesis project may lead to the possibility of using high frequency (hence, physically small) transducers operated at the high frequency as a carrier and measuring the phase shift incurred on the low, modulation frequency due to the wind components. Since there is no restriction on this low, modulating frequency, it will be possible to monitor much higher wind velocities than are presently measurable with existing acoustic anemometers.

II. BASIC THEORY OF ACOUSTIC ANEMOMETRY

Sound emitted from a point source into a still, uniform atmosphere will propagate as a spherical wave concentric with its source, if the source is small compared to the wavelength of the sound in the medium in which it is traveling. Any motion of the atmosphere will be superimposed on the velocity of the progressing wavefront.

If two receivers are placed equidistant from the source, a component of wind in the plane of the transmitter and receivers can be measured by detecting the phase difference between the signals picked up at the two receivers. If two additional receivers are placed equidistant from the transmitter in a plane perpendicular to the plane formed by the transmitter and the first two receivers,(See Figure 1) these four receivers will lie on a plane of constant phase in a no wind condition.

Referring to figure (1), u, v, and w are wind components along three mutually perpendicular axes x, y, and z, of which x and y are the two horizontal axes along which wind components are to be measured. Following the derivation by Kaimal,[1] a spherical sonic wave traveling in a gaseous medium which is itself in motion can be expressed:

$$(x - ut)^2 + (y - vt)^2 + (z - wt)^2 = (ct)^2 \qquad (1)$$

[1] Reference 3, p. 3-5.

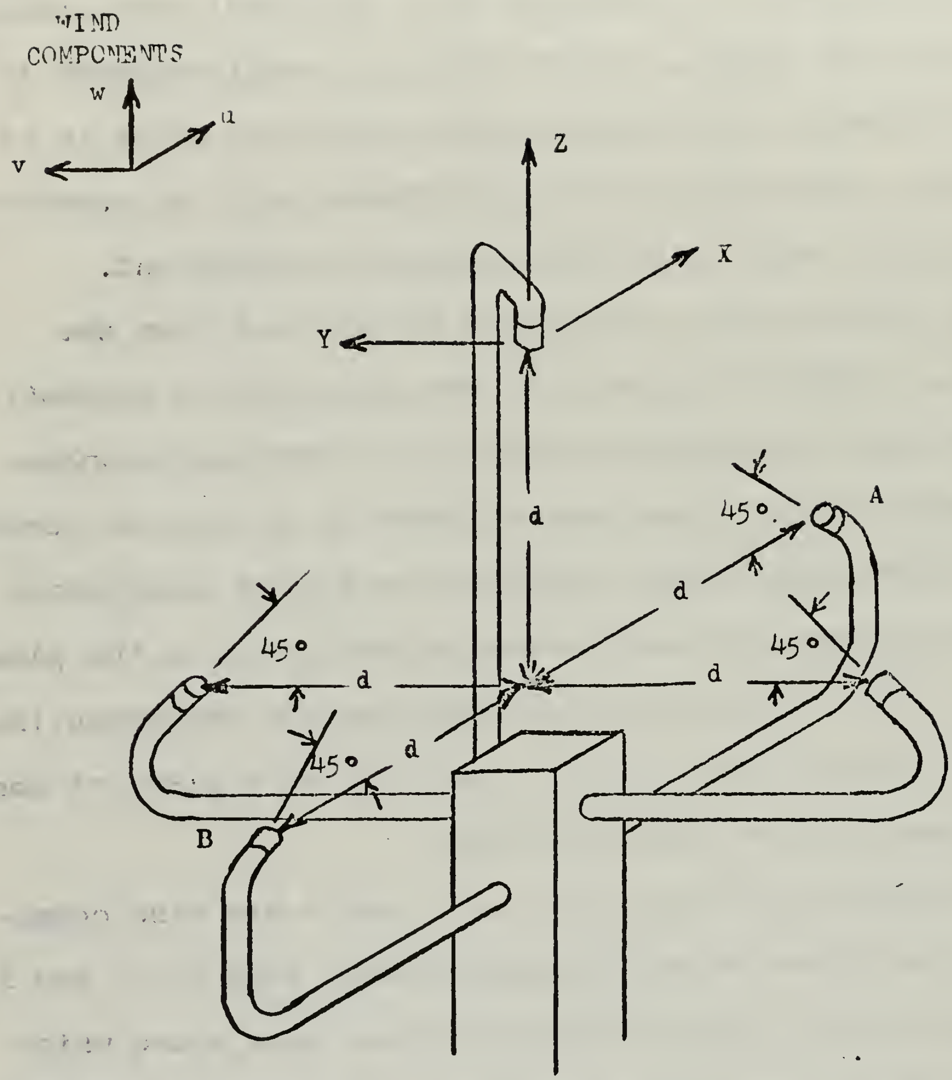

FIGURE 1. TRANSDUCER ARRAY

In this equation x, y, z, u, v, and w are as defined above; t is time; and c is the velocity of sound in the gaseous medium at the ambient temperature of operation.

Rearranging the previous equation in quadratic form results in

$$t^2\,(u^2 + v^2 + w^2 - c^2) - 2t\,(ux + vy + wz) + (x^2 + y^2 + z^2) = 0 \tag{2}$$

The time for a wavefront to travel from the transmitter to receiver A(x = d, y = 0, z = -d) is

$$t_a = d\,\frac{(u - w) + (u - w)^2 - 2(u^2 + v^2 + w^2 - c^2)^{\frac{1}{2}}}{u^2 + v^2 + w^2 - c^2}$$

By neglecting higher order terms this equation can be approximated

$$t_a \cong d\,\frac{(u - w) + \sqrt{2}\,c\left[1 - \frac{uw}{2c^2} - \frac{u^2 + 2v^2 + w^2}{4c^2}\right]}{u^2 + v^2 + w^2 - c^2} \tag{3}$$

Using a similar analysis, the time of arrival of a wavefront at receiver B (x = -d, y = 0, z = -d) is

$$t_b \cong d\,\frac{(-u-w) + \sqrt{2}c\left[1 + \frac{uw}{2c^2} - \frac{u^2 + 2v^2 + w^2}{4c^2}\right]}{u^2 + v^2 + w^2 - c^2} \tag{4}$$

The difference in arrival time at receivers A and B is found by subtracting (3) from (4).

$$\Delta t_x = \frac{2du\,(1 - \frac{w}{\sqrt{2c}})}{c^2 - u^2 - v^2 - w^2} \tag{5}$$

Now, a first order approximation can be made.

$$\Delta t_x \cong \frac{2du}{c^2} \tag{6a}$$

Analogously in the y direction

$$\Delta t_y \cong \frac{2dv}{c^2} \tag{6b}$$

Also, it will be assumed for the purposes of this thesis that the vertical z axis component of wind is negligible.

The foregoing first order approximations can be made because as can be seen in equation (5) wind components of less than 35 meters per second are more than two orders of magnitude smaller than the velocity of sound and thus the error would be less than 1%. Likewise for wind components of less than 70 meters per second the error would be less than 4%.

By appropriate approximations it can be shown that near $300^\circ K$ the speed of sound changes by $\pm 1\%$ for a $\pm 3^\circ C$ change in ambient air temperature. This means that for extreme temperature ranges of $\pm 40^\circ C$ the wind speed readout could have an error of nearly 14%.[1] By incorporating an automatic temperature compensating system using temperature sensitive resistance elements, this error can be greatly reduced. However, for the purposes of this thesis this will not be done as no means would readily be avail-

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[1] Reference 1, p. 7.

able to test the apparatus under these extreme temperature conditions. A provision will be made for manually adjusting the calibration of the wind speed readout for the current ambient temperature.

From equation (6) it can be seen that the transit time is directly proportional to the transducer transmitter to receiver separation. For this reason, any small deviation from the nominal transducer separation caused by thermal expansion or vibration of the supporting members would result in a corresponding measurement error. For example, if the transducer were displaced by ± 0.5 centimeters (and $d = 50$ centimeters) the measurement error would be $\pm 1\%$.

Another source of error is the wake turbulence caused by the transducer array supporting members. It is estimated that if the ratio of transducer separation to transducer diameter is greater than 40 the aerodynamic errors will not exceed 4%.[1]

Probably the most difficult problem to solve is the minimization of noise introduced into the system. Stray acoustic signals can enter the system through the array structure. Electrical noise may be picked up in many areas, especially along the connecting cables and in the tuned circuits. "Lastly , since the device operates continuously, it has a noise bandwidth equal to the signal bandwidth, and extraneous sonic energy such as might be encountered

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[1] Reference 6.

from nearby aircraft must be minimized or tolerated as an error source."[1]

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[1] Reference 1, p. 9.

III. DESIGN

A. GENERAL SYSTEM DESCRIPTION

As shown in figure (2), a 40 kilohertz transmitter modulated at 2 kilohertz (Khz) drives a transmitting transducer with 100 milliwatts (including sidebands) of output power. There are four receiving transducers arranged in the manner as described in Chapters I and II. More discussion on the characteristics of these ultrasonic transducers will be made in a later section of this thesis. Each receiving transducer is shunt tuned with a 8-20 millihenry choke. Immediately following each tuned receiving transducer is a cascode preamplifier featuring a field effect transistor (FET) input. These preamplifiers provide enough gain (approximately 25db.) to keep the signal level well above the noise pickup in the cable connections to the subsequent ultrasonic amplifier and detector stages. The ultrasonic amplifier for each receiver channel is a two stage feedback amplifier which develops 40 decibels of voltage gain and exhibits high input impedance and low output impedance for driving the following detector circuitry.

Following the ultrasonic amplifier, a detector stage removes the 40 Khz carrier and passes the 2 Khz signal directly to the pulse forming circuitry or, in the South and West channels, through a phase inverter prior to entering the pulse forming circuits. By limiting, differentiating, and clipping, a triggering pulse is obtained which corresponds to the positive going zero crossing of the 2Khz

BLOCK DIAGRAM OF THE ACOUSTIC ANEMOMETER

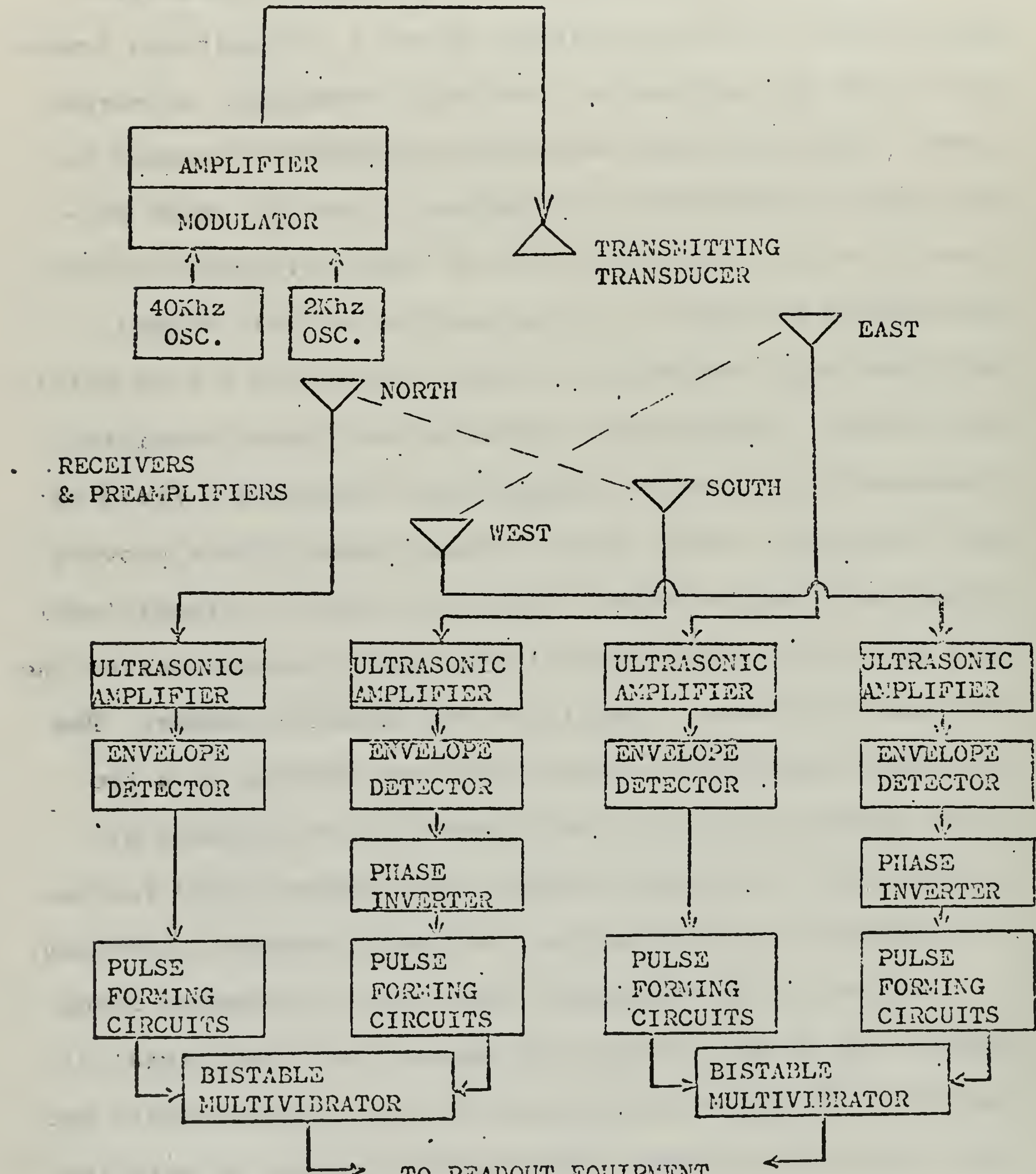

FIGURE 2

signal (or as applicable, the positive going zero crossing of the inverted signal). An unsymmetrically triggered bistable multivibrator is used to obtain phase comparison between signals from two diagonally opposite receivers in the transducer array. (Obviously, a similar bistable phase comparator is used for the other pair of diagonally opposite receivers.)

The output of the multivibrator is a 2 Khz rectangular wave that has a positive or negative direct current level that corresponds linearly to the phase difference of the two received signals and hence represents the speed of the corresponding wind component. This direct current level can be obtained by passing the rectangular wave through some type of low pass circuit such as a d.c. milliammeter or a simple RC filter. It can be seen that since one channel in each diagonally opposite pair of receivers incorporates phase inversion, the d.c. level will be zero with no wind since the 180^{o} phase delay will generate a multivibrator output that is a symmetrical square wave. Since the phase comparison method used in this thesis is based on the time difference of zero crossings in the two channels being compared, the output is linearly dependent on the phase difference and nearly independent of amplitude fluctuations of the received signals.

The analog nature of this output lends itself to a variety of readout systems. The North South and East-West wind components can be recorded individually on strip re-

corders or monitored with center zero milliammeters. The readout for this thesis is obtained by driving the vertical and horizontal deflection plates of a cathode ray tube to obtain a wind vector representation on the scope face.

The transmitter was mounted on two plug in circuit boards and the receiver components were mounted four circuit boards. With more extensive use of miniature components the transmitter could have been placed on one board and three boards would have easily sufficed for the receivers. Obviously, the whole system could be built with integrated circuitry in much less space but the practicality of this must be considered in view of the fact that it is improbable that these anemometers would be built in large quantities and that the savings in space would not usually be a prime factor. (See Appendix C)

B. TRANSDUCERS

Initially, some consideration was given to using small ceramic or crystal piezoelectric transducers for use in the 100 and 500 kilohertz frequency range. However, due to the limited time available for experimentation and the fact that no acceptable transducers were readily available in this range, the decision was made to use a commercially available (and inexpensive) 40 kilohertz piezoelectric transduc-

er.*

The transducers are manufactured by Massa Industries of barium titanate and are mounted in a metal casing less than 1 inch in diameter. (See Appendix E)

These transducers are resonant at 40 kilohertz when series or parallel tuned with an 18 millihenry choke exhibit a bandwidth of about 4 kilohertz. The maximum continuous power rating of these units is 500 milliwatts when operated as a transmitter. The transmitting transducer was series tuned and presents a 400 ohm load so that the transmitted power required could be obtained with relatively low voltages. The receiving transducers were shunt tuned primarily because of the somewhat higher gain achieved. This parallel method of tuning gives a nominal impedance of 40 kilo-ohms. These transducers proved satisfactory, however, a wider beam width for the transmitter would have been a welcome feature.

C. TRANSDUCER ARRAY

In the interests of saving time and money, the standard for the transducer array was constructed from a "four

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* It should be emphasized here that the higher frequency, physically smaller transducers would have enabled this experimenter to construct a much small (and more desirable) transducer array. Fewer applications are found for ultrasonic transmission in air than in liquids or solids. This is primarily due to the high attenuation of ultrasound in air and the problems of impedance matching to the gaseous medium. This partly explains the very limited choice of transducers available at this time.

by four" wood stock supported in a vertical position by four "two by four" wood legs (See Appendix B). An additional advantage of the wooden standard is that some acoustic isolation is provided between the metal supporting arms of the transducer array.

The supporting arms of the transducer array were built of 3/4 inch diameter electrical metallic tubing ("thinwall" conduit). The transducers are mounted over the open ends of the conduit and are firmly held in position by binding with rubber tape. Installed directly underneath the receiving transducers and inside the conduit and are firmly held in position by binding with rubber tape. Installed directly underneath the receiving transducers and inside the conduit supporting arms are the tuning inductors and cascode preamplifiers. Power is supplied to the preamplifiers via the coaxial connecting cables. The output of the preamplifiers is transmitted to the ultrasonic amplifier "on top" of the d.c. power supply voltage.

At this point a quick return to the theory of acoustic anemometry is required. By using the relationship

$$\Delta\phi = \omega\Delta t = 2\pi f \, \Delta t \tag{7}$$

and equation (6a) we can derive:

$$\Delta\phi = \frac{4\pi f d u}{c^2} \tag{8}$$

Now if we let the maximum phase shift at the maximum measurable wind velocity be $\Delta\phi = \pm\,\pi$ we arrive at the

following

$$d = \frac{c^2}{4F\, u_{max}} \tag{9}$$

It can be shown by substituting appropriate values for frequency, maximum wind velocity, and the speed of sound, that a separation distance of 0.5 meters will allow a wind speed of approximately 30 meters per second, if the frequency at which the phase measurement is made is 2 kilohertz. This 2 kilohertz frequency is the maximum modulation frequency allowable to remain within the bandwidth of the tuned transducers. The transducer separation distance "d" (See figure 1) of 0.5 meters was used in the construction of the transducer array. Final adjustment resulted in accuracy of transducer placement to within ± 3 millimeters.

D. TRANSMITTER

The transmitter (Figure 3) consists of four basic circuits: a 40 kilohertz carrier frequency oscillator, a 2 kilohertz modulation frequency oscillator, a modulator, and an output amplifier.

Several oscillator designs were tested prior to choosing a two transistor oscillator tuned at the 40 kilohertz carrier frequency. This circuit has excellent frequency stability and more than ample output voltage.

The 2 kilohertz modulation frequency oscillator is a twin tee oscillator with very good frequency stability. The one volt output is quite sufficient for modulation purposes after being sent through an emitter follower.

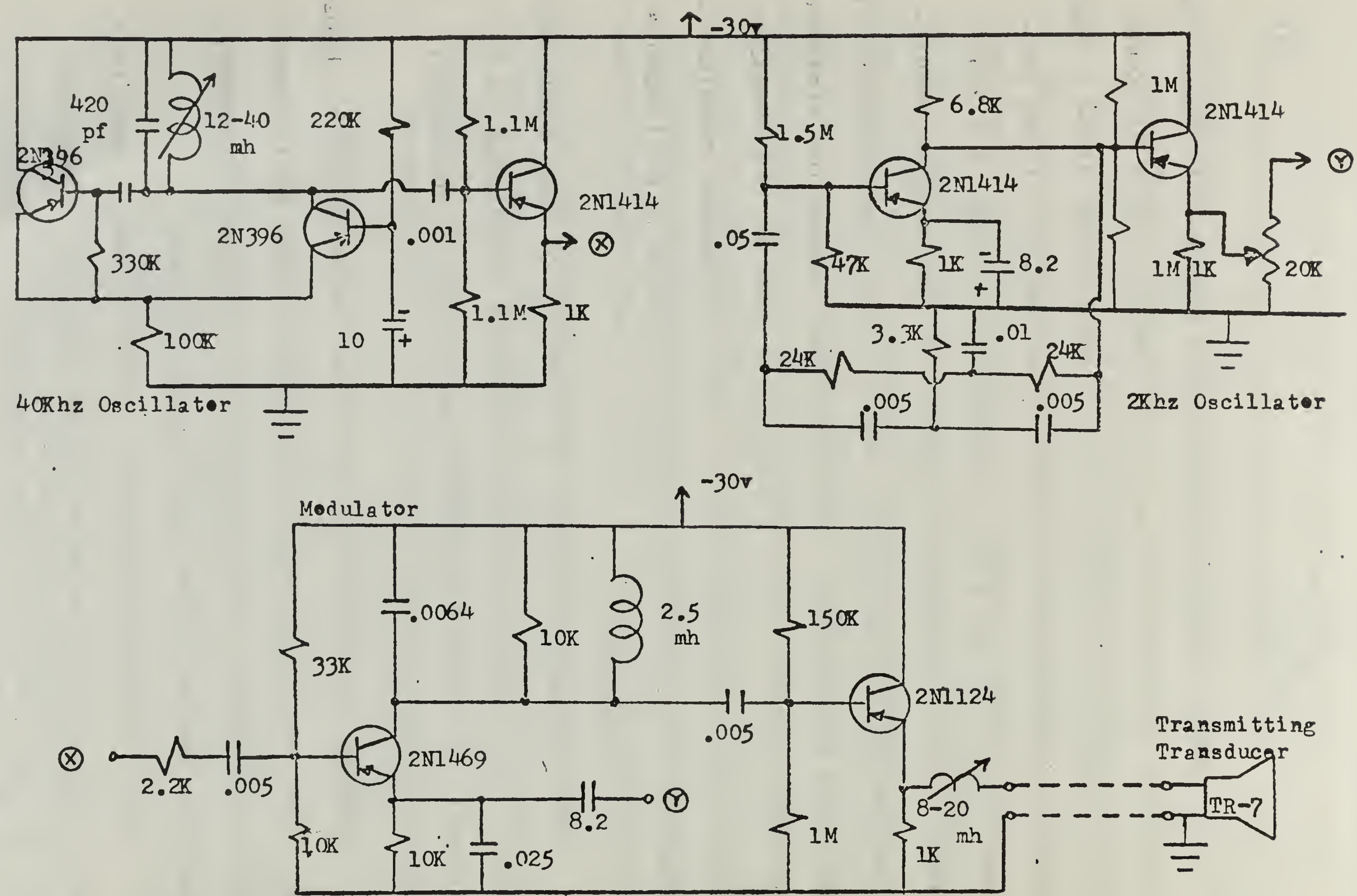


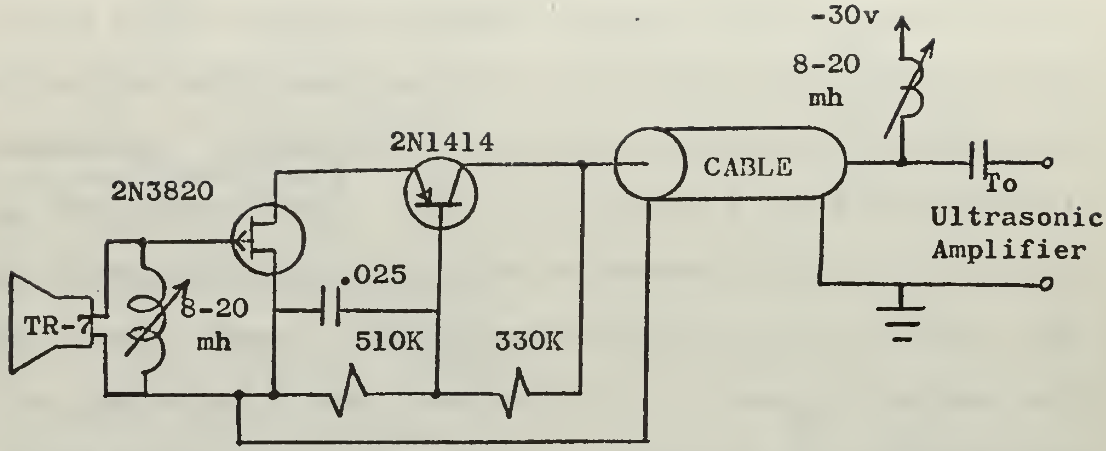
FIGURE 3. TRANSMITTER SCHEMATIC DIAGRAM

The modulator is a single transistor stage with the 40 kilohertz carrier applied at the base and the 2 kilohertz modulation injected at the emitter. The emitter is bypassed to ground for the carrier frequency. The modulation may be varied between zero and approximately 95 per cent with a potentiometer at the modulation frequency input. The output of the modulator is parallel tuned circuit with the center frequency at 40 kilohertz and a bandwidth of approximately 4 kilohertz. Both oscillators drive the modulator through emitter follower isolation amplifiers. The output of the modulator drives an emitter follower for impedance matching to the series tuned transmitting transducer. This series tuned combination presents a load of 400 ohms (See Appendix E). The power delivered to this load varies from 250 milliwatts at zero modulation to somewhat over 100 milliwatts at 95 per cent modulation.

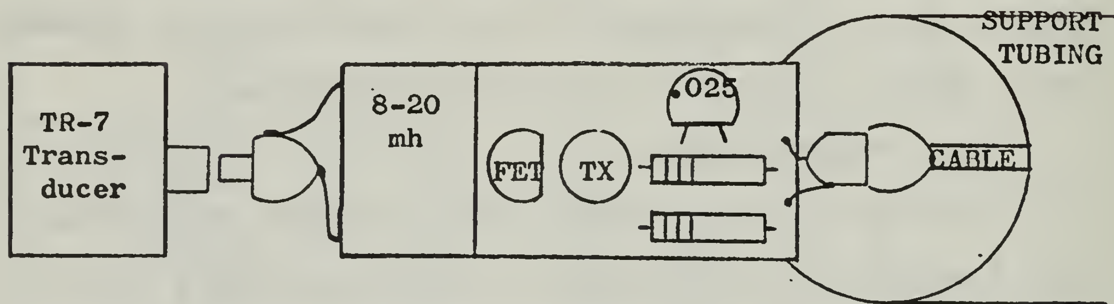
E. PREAMPLIFIERS

At first it was thought that the shunt tuned receiving transducers could produce sufficient signal to drive the ultrasonic amplifier through the connecting coaxial cable. After considerable experimentation it was determined that preamplifiers were needed to enable the signal to overcome the noise pickup in the cable.

Cascode amplifiers with field effect transistor (FET) inputs were constructed on small circuit boards suitable for inserting into the support tubing directly behind the tuned receiving transducers (See Figure 4 and Appendix D).



PREAMPLIFIER SCHEMATIC DIAGRAM



PREAMPLIFIER INSTALLATION

FIGURE 4

Power for the preamplifiers was supplied on the coaxial cable; the output signal was superimposed on this d.c. level. The load for the preamplifiers was uniquely achieved by resonating the capacitance of the connecting cable by a shunt tuning inductor. The actual Q of this load was not measured but a noticeable reduction in noise level was obtained. At the input to the ultrasonic amplifier the signal level was 100 millivolts peak to peak.

F. RECEIVERS

Ultrasonic amplifier. - A two stage series-shunt feedback amplifier was designed to offer high input impedance across the tuned preamplifier load and also provide low output impedance for driving the subsequent detector stage. This ultrasonic amplifier has excellent frequency response and provides 38 decibels of voltage gain. At this point, it was noticed that considerable amplitude modulated signal was observable at the power supply. Instead of attempting to isolate all of the receiver and transmitter stages, a separate power supply with a common ground was used for all receiving circuitry, including the preamplifiers and phase detectors.

Envelope detector. - A semiconductor diode and a simple resistor-capacitor low pass filter serve adequately as an envelope detector.

Audio amplifier. - Two stages of audio amplification of the 2 kilohertz signal follow the detection circuit. The first stage is a common emitter which provides 40 decibels

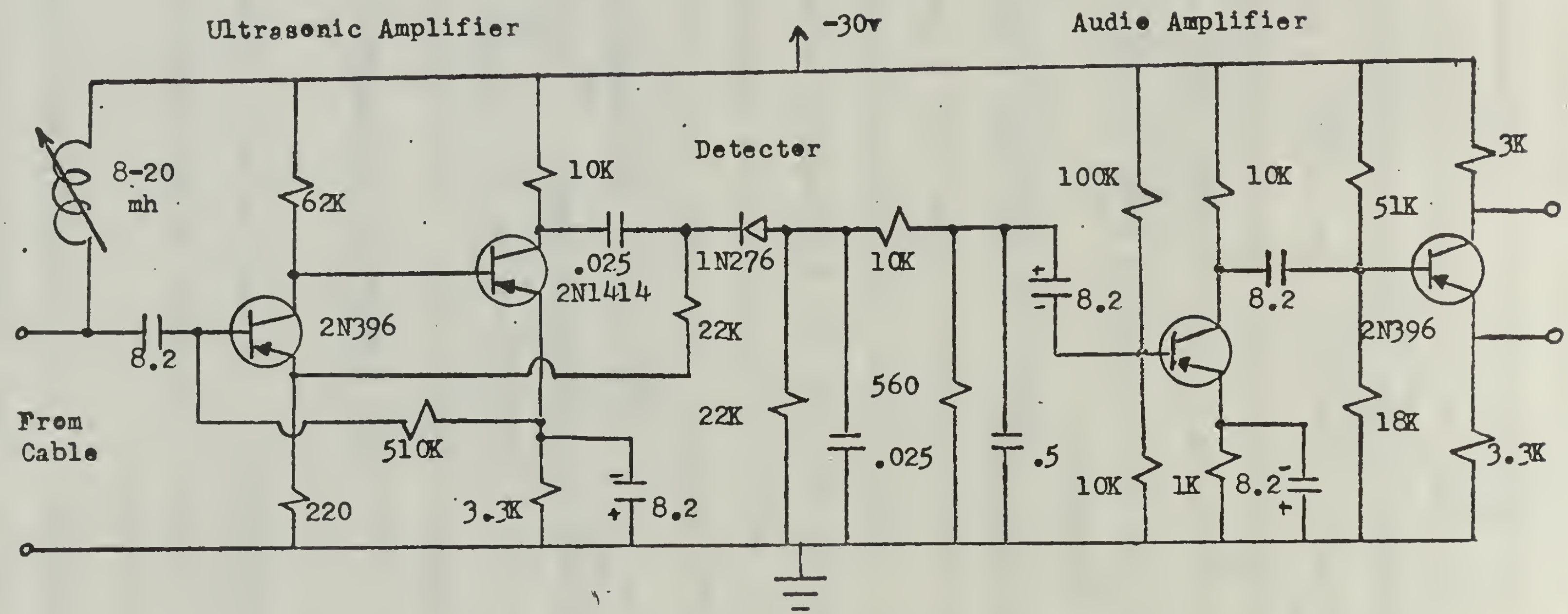


FIGURE 5. RECEIVER SCHEMATIC DIAGRAM

voltage gain. This stage drives an amplifier that is designed for unity gain whether the output is taken from the emitter or the collector (for phase reversal). This allows the required 180° phase difference for diagonally opposite receivers.

G. PULSE FORMING CIRCUITS

Square wave generator. - An amplifier consisting of two common emitter stages is overdriven by the output from the audio amplifier. This results in a symmetrical square wave with a voltage swing of approximately 25 volts. (See Figure 6).

Differentiator and Clipper. - The output from the square wave generator is processed through a simple capacitor-resistor differentiator. The negative pulses derived from the differentiation of the square wave are clipped effectively by a semiconductor diode across the differentiator output.

H. PHASE COMPARATOR

All of the previously discussed receiver circuitry is common to each of the four channels; all of the following circuitry is shared by each of the two channel pairs corresponding to the two pairs of diagonally opposite receiving transducers (See Figure 2).

Bistable multivibrator. - An unsymmetrically triggered bistable multivibrator (flip-flop) was designed to produce a rectangular wave output with a voltage swing of 23 volts. The duty cycle of this rectangular wave is directly propor-

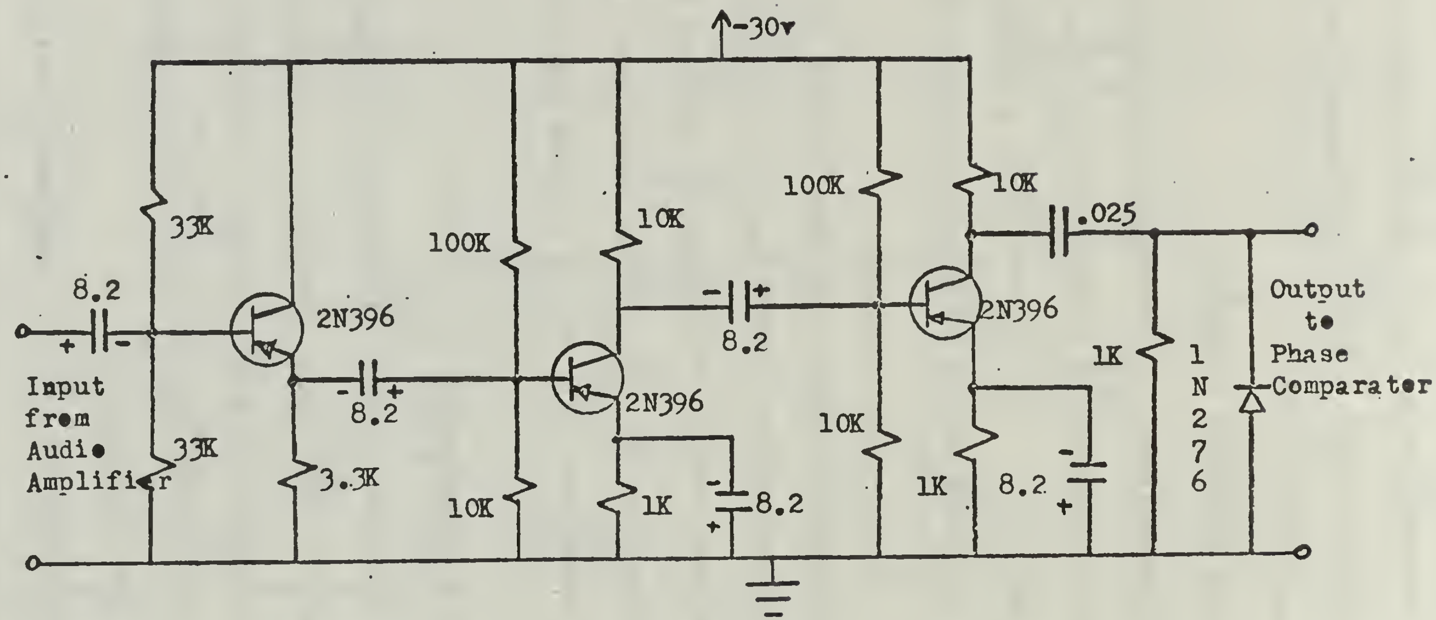


FIGURE 6. PULSE FORMING CIRCUIT

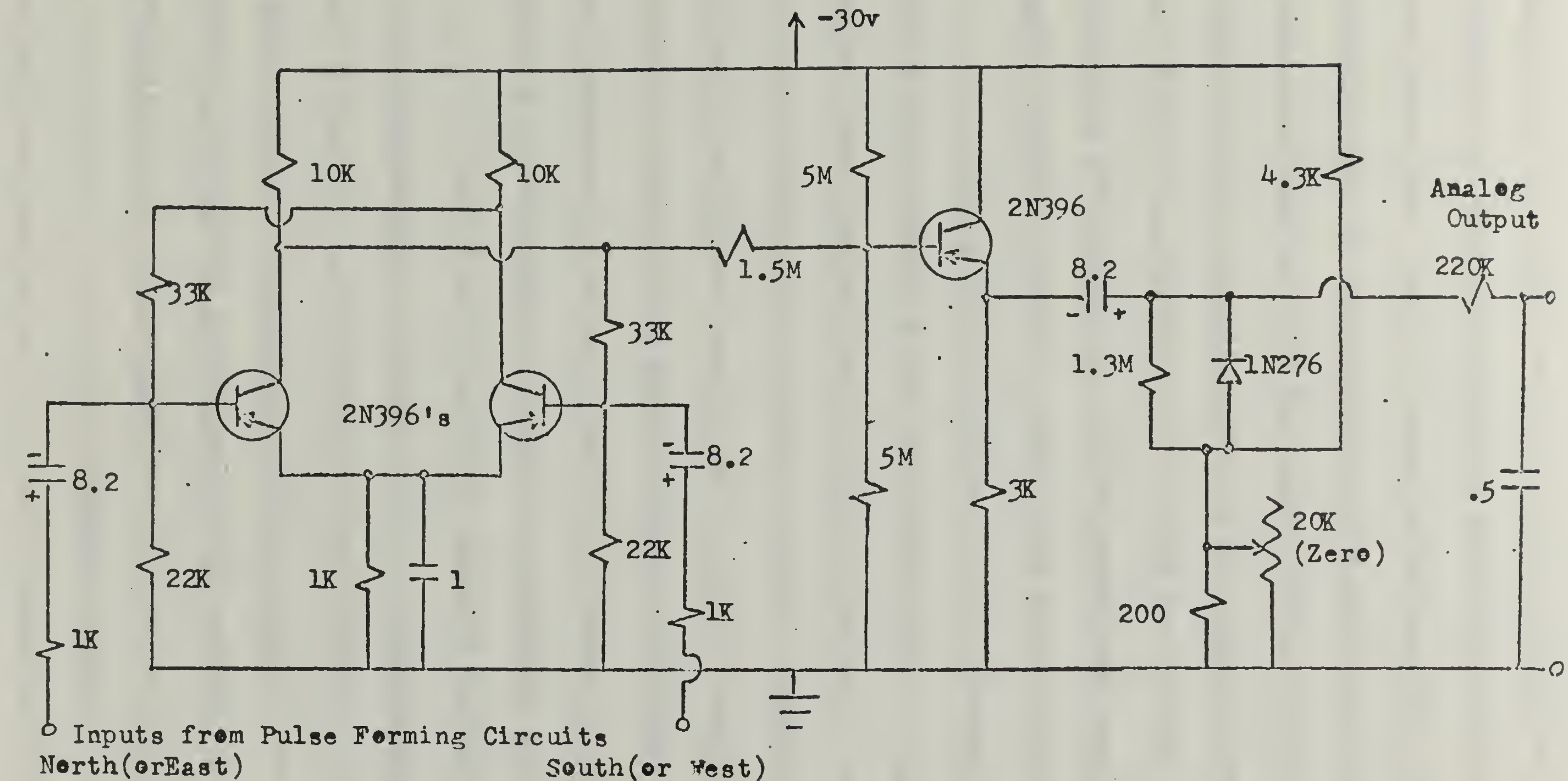


FIGURE 7. PHASE COMPARATOR

tional to the appropriate velocity component of the wind. With a no-wind condition, the flip-flop is triggered alternately by the pulses from two diagonally opposite channels to form a symmetrical square wave. Any wind component will vary the relative time difference of the triggering pulses and hence the duty cycle of the rectangular wave output. This rectangular wave has a direct current component that is the analog of the wind component. As the wind approaches the maximum measurable velocity (30 meters/sec), the rectangular wave will have a direct current component which will approach ± 11.5 volts as appropriate.

Clamper. - The output of the bistable multivibrator is clamped to a level which gives zero direct current output for no wind. If there were no position errors in the transducer array, the no wind output would be a perfect square wave. However, certain errors are likely, therefore, a means for correcting these errors is provided by making the clamp reference voltage variable with a potentiometer in a voltage divider network (See Figure 7).

Low pass filter. - The clamped rectangular wave is passed through a simple resistor-capacitor low pass filter to recover the direct current component. At the output terminal, the voltage level may vary between ± 0.9 volts as a direct analog of the corresponding wind velocity component.

I. READOUT METHODS

Initial monitoring of system response was accomplished by observing on an oscilloscope the output from the low

pass filter. It was found that a more desirable presentation was acheivable by disabling the oscilloscope horizontal sweep circuitry; the low pass filter output can then be used to deflect the trace in either the vertical or horizontal directions. This obviously leads to a quite satisfactory means for displaying the wind vector by applying the output of the North-South axis channels to the vertical deflection plates of the oscilloscope and the East-West axis outputs to the horizontal deflection plates. With the proper adjustment of horizontal and vertical sensitivity to correspond to an appropriate scale factor, the wind speed and direction can be read directly by noting the position of the deflected oscilloscope trace. To further enhance the feeling of viewing a vector presentation, a relay was incorporated to make and break the input to the oscilloscope so that the beam would periodically return to zero and thereby draw a vector on the oscilloscope face. This method did not function as well as desired; it was important that the relay contacts for both the horizontal and vertical inputs were in perfect synchronization or the vector drawn would not be a straight line. Electronic switching could easily alleviate this problem.

Since the maximum measurable wind is 30 meters per second and corresponds to an output 0.9 volts, a scale factor can be determined as follows:

$$30 \text{ m/s} = 58.4 \text{ Kts}$$

$$\text{Scale Factor} = \frac{58.4}{0.9} = 65 \text{ Kts/volt}$$

If we allow each centimeter of deflection to indicate 10 Kts, we must adjust the sensitivity to $\frac{10}{65} = 154$ mv/cm for both the horizontal and vertical directions.

IV. RESULTS & DISCUSSION

After completion of the design and construction phases of the "Solid State Amplitude Modulated Acoustic Anemometer", initial testing was achieved by the very crude method of directing the wind created by a large portable fan through the transducer array. This produced a very turbulent reading of approximately 12-15 miles per hour, which seemed reasonable.

One pair of transducers (North-South channels) was installed along with the transmitting transducer in the West Coast Research Corporation 3.5 feet by 5 feet academic wind tunnel at the Naval Postgraduate School. It was hoped that by using the wind tunnel velocity as a reference, a calibration chart could be plotted. However, it was immediately evident upon activating the wind tunnel that the ambient noise and vibration level was so great that it would render all readings meaningless.

After the abandonment of the wind tunnel tests, the transducer array was reassembled on the roof of Spanagel Hall at the Naval Postgraduate School in order to monitor the acoustic anemometer performance in a more natural wind environment. This location offered the best locally available combination of unobstructed natural wind flow and electrical and physical facilities.

Noise picked up in the system caused an output random error of approximately $\pm$ 5 knots with no wind conditions. This error was less bothersome when the wind velocity was

over about 15 knots but it was still superimposed on the readout. This noise generated error was the primary problem that plagued the author throughout the development of the circuitry. Although not experimentally confirmed, it is felt that a possible source of the signal fluctuations may be random interference and reinforcement of the transmitted signal. These fluctuations could be attributed partly to atmospheric disturbances and partly to the transmitting transducer not being a true point radiator.

For initial qualitative monitoring of system response, one coordinate axis of the acoustic anemometer was aligned with the prevailing wind. This arrangement allowed observations of maximum oscilloscope deflection for a given wind. The transducer array position was then reversed with respect to the wind direction. This simulation of a 180 degree wind change was used for observing bidirectional linearity. Within reading errors due to the noise fluctuations, wind observations in either direction seemed to indicate identical sensitivities.

During the infrequent periods when acceptable system noise level and appreciable natural wind velocity coincided, observations were made of oscilloscope wind vector presentation as the transducer array was rotated. The wind components were seen to be nicely displayed as a vector. As the wind direction changed or the transducer array was rotated the oscilloscope wind vector changed appropriately.

At no time during the testing were winds available

that approached the designed velocity maximum. However, it is felt that the present transducer array supporting structure would be caused to vibrate at an unacceptable level in winds over 40 knots.

The cost of the components of the acoustic anemometer was as follows:

5	Transducers	$25.00
11	2N 1414	8.91
32	2N 396	19.52
4	2N 3820	15.00
11	Inductors	23.10
Miscellaneous Resistors & Capacitors		30.00
5	15 ft. cables	8.55
6	Plug-in circuit boards & receptacles	36.78
41	Transistor Sockets	9.74
Miscellaneous		20.00
TOTAL		$196.60

This represents a total unit cost that is quite reasonable for measurement equipment of this type. Even with the further improvements needed it seems likely that acoustic anemometers of this type could be manufactured for less than $250.00 each.

In summary, the tests conducted so far indicate that the system is capable of performing as the theory predicts.

With further suppression of system noise, an inexpensive and practical amplitude modulated acoustic anemometer could be developed.

V. RECOMMENDATIONS

It has been demonstrated to the author's satisfaction that amplitude modulated acoustic anemometers are quite feasible and could be easily miniaturized and inexpensively meanufactured.

Although the design and circuitry of this thesis functioned somewhat less than satisfactorily, it is felt that with some additional emphasis on shielding, stage isolation, and circuit stability a highly satisfactory system could be developed with very little increase over the previously enumerated costs. A critical problem in this system was pickup in the connecting cables. It is apparent that considerable noise is introduced into the system and this noise is the major contributor to the jittery output signal. Additional improvements can be made by further increasing the transmitter power output and insuring that a very stable modulation envelope is produced. Certainly improvement could be achieved by using a transmitting transducer that exhibited a more nearly hemispherical radiation pattern than the TR-7.

The author envisions an ultimate acoustic anemometer design using the techniques explored in this thesis which would consist of very small transducers in an array with diagonal separations of less than six inches. However, it seems unlikely that such an instrument could prove to be useful in missile and aircraft aerodynamic studies due to the vibration levels of the environment.

It may be pointed out here that Air Force Cambridge Research Laboratories has recently developed a pulse type acoustic anemometer[1] which significantly improves the signal to noise ratio and decreases the effects of transducer array vibration. Although the Cambridge Laboratories equipment is much more complex and costly than the equipment developed in this thesis, pulse techniques in acoustic anemometers offer great promise and deserve further investigation, as well as the amplitude modulation techniques presented in this thesis.

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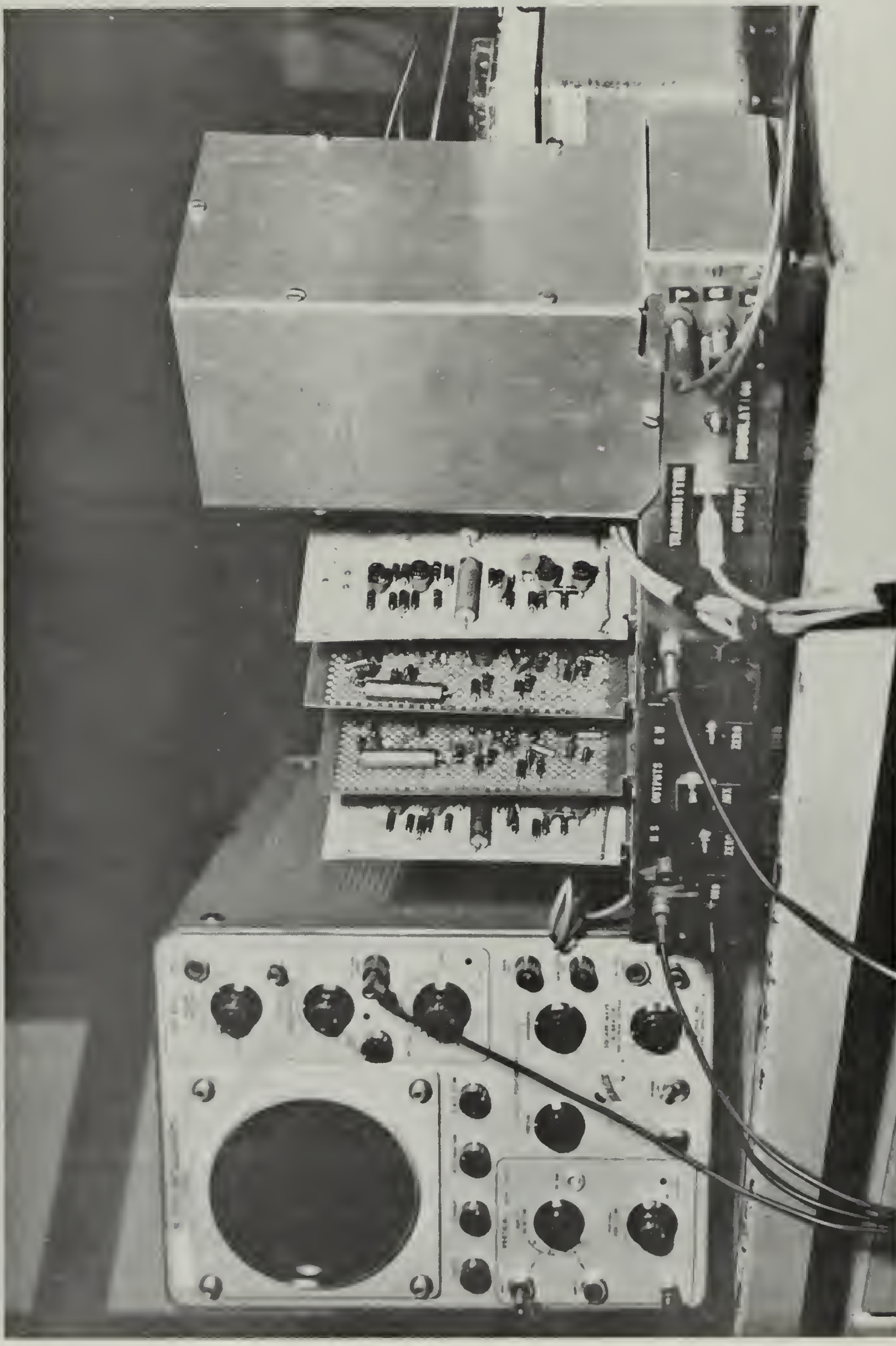
APPENDIX A

SPECIFICATION SUMMARY

Carrier frequency	40 Khz
Modulation frequency	2 Khz
Power requirement	3.6 watts, 30vdc
Transducer array	base 50"x50" height 84"
Electronics package	5"x17"x10"
Measurement range (designed)	0-30 meters/second
Output	Oscilloscope wind vector presentation

APPENDIX B



APPENDIX D

REMOTE CONTROL

ULTRASONIC TRANSDUCERS

MODELS TR-7 TR-41

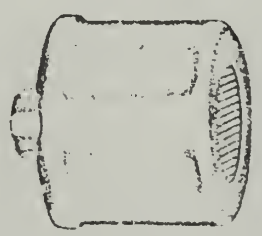
The MASSA Ultrasonic Transducers, Models TR-7 and TR-41 are transmitters and/or receivers developed for a wide variety of indoor and outdoor remote control applications. These units were originally designed especially for Original Equipment Manufacturers where small, efficient, low-cost transducers are required to eliminate direct connection between the control device and the equipment being controlled.

The smaller unit, model TR-7 which resonates at 40kc, is ideal for use in remote control TV tuners, burglar alarm systems and in carrier frequency communications. Control at distances up to 100 feet or more is easily obtained with this model. A phono-type connector is used on the terminal end of the model TR-7.

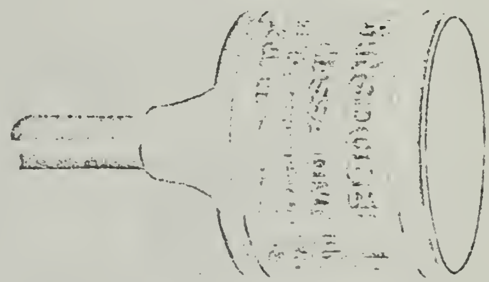
The larger waterproof unit, model TR-41, resonates at 23kc, and is used primarily for outdoor applications, such as automatic garage door openers. This unit is supplied with an open end cable.

APPLICATIONS: Burglar Alarm Systems • Carrier Frequency Communications • Short Range Distance Measurement of Objects (Sonar, Air) • Proximity Detectors.

(Over)



TR-7



TR-41

SPECIFICATIONS

MODEL	TR-7	TR-41
PHYSICAL SIZE	1" dia. x 1" long	1-5/16" dia. x 1" long and 12" length of cable
RESONANT FREQUENCY	40 kc ±1/2 kc	23 kc ±1 kc
BAND WIDTH	4 kc (with tuning choke)	4 kc (with tuning choke)
TRANSMITTING SENSITIVITY	+20 db vs 1 μbar at 1 ft. (100 mw available power)	+30 db vs 1 μbar at 1 ft. (100 mw available power)
RECEIVING SENSITIVITY	−60 db vs 1 volt per μbar untuned (see curves for tuned sensitivity)	−56 db vs 1 volt per μbar untuned (see curves for tuned sensitivity)
CAPACITANCE	850 mmf	850 mmf
DIRECTIONAL CHARACTERISTICS	total beam angle 60° at 6 db down points	total beam angle 70° at 6 db down points
POWER RATING	1/2 watt steady state; 5 watts 10% duty cycle	2 watts steady state; 20 watts 10% duty cycle
TEMPERATURE RATING	less than 2% change in resonant frequency and less than 5% change in capacity over temperature range 0°F — 130°F	

d U S A Massa Division reserves the right to change prices and specifications without notice. 772 10 65

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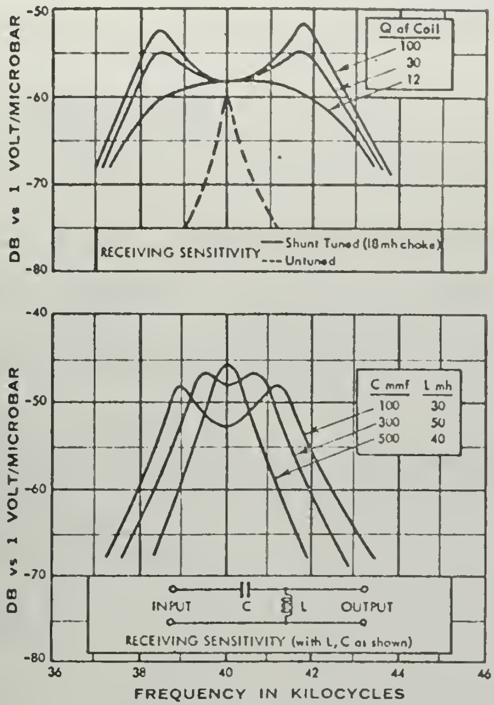
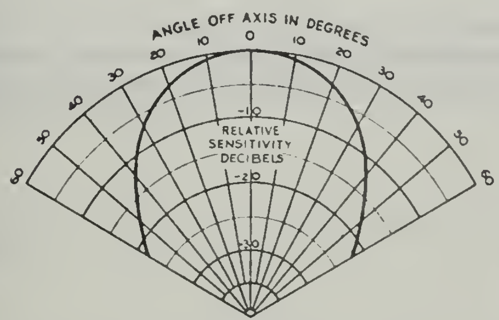
280 LINCOLN STREET, HINGHAM, MASSACHUSETTS 02043

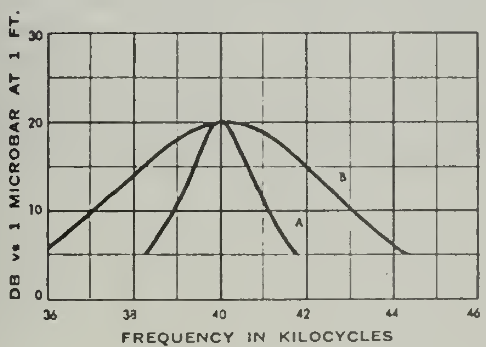
Model TR-7



RECEIVING RESPONSE



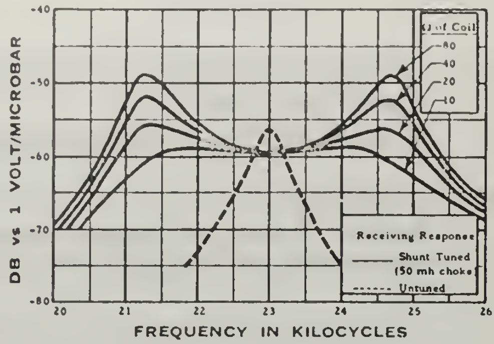
DIRECTIONAL RADIATION PATTERN AT 40 KC



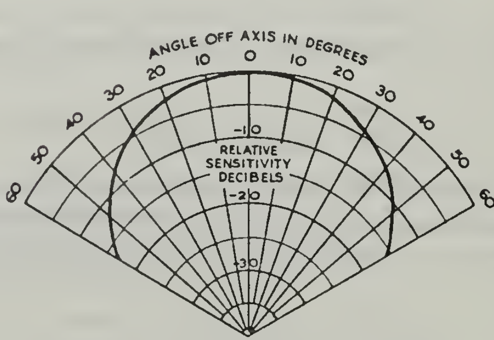
TRANSMITTING RESPONSE
(100 milliwatts available power)

A. Untuned (4000 ohm impedance source)
B. Series tuned 18 mh (400 ohm source) or shunt tuned 18 mh (40,000 ohm source)

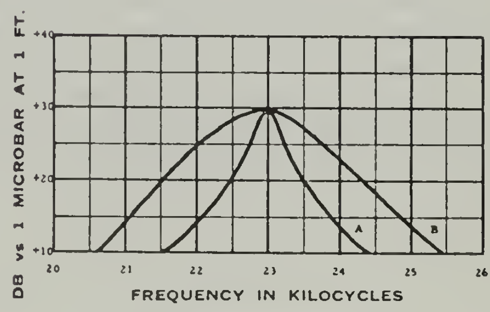
Model TR-41



RECEIVING RESPONSE



DIRECTIONAL RADIATION PATTERN AT 23 KC



TRANSMITTING RESPONSE
(100 milliwatts available power)

A. Untuned (10,000 ohm impedance source)
B. Series tuned 50 mh (2500 ohm source) or shunt tuned 50 mh (25,000 ohm source)

Note: Massa Division does not have available diagrams or schematics for doppler or remote control systems, being manufacturers and suppliers of these transducers to Original Equipment Manufacturers for use in a variety of applications.

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13. ABSTRACT

In recent years considerable research has been directed toward developing wind measuring devices that eliminate the need for moving parts. This thesis proposes a method using amplitude modulated ultrasound to provide greater dynamic wind velocity measurement range and at the same time decrease the cost and complexity of the system. The theory, design, and implementation of the system are presented and the limited results are discussed.

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Ultrasonic						
Wind measurements						

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